Development of semiconductor solid-state detectors with sub-100ps time resolution.

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On behalf of the **TT-PET collaboration**

The fast silicon pixel detector

- At the beginning of the LHC era, the RPC was the only detector capable of sub-100ps time resolution.

- Silicon pixel technology was focusing on tracking, power consumption and radiation hardness, with a time resolution in the range from few ns to some tens of ns.

- The roadmap for the development of **silicon pixel detectors with a 100ps (or better) time resolution** will the described **through the experience of the TT-PET collaboration**.

The TT-PET project

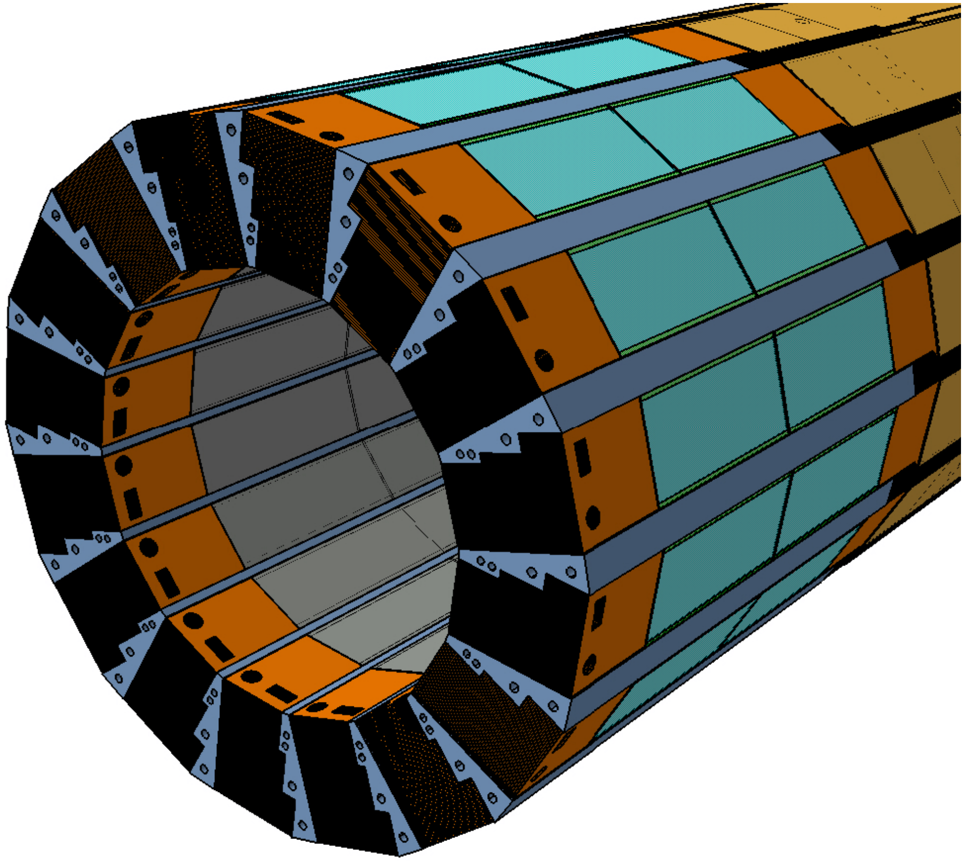
A 3-year project financed by SNSF to produce a PET Scanner for small animals **based on silicon detector technology,** insertable in an MRI machine and with 30ps RMS time resolution. The project started in March 2016.

The TT-PET collaboration:

- University of Geneva .
- University of Bern
- Hôpital cantonale de Genève
- INFN of Roma Tor Vergata
- CERN
- Stanford University

Other collaborators:

- IHP Microelectronics



Targets of the TT-PET project

1. Make a 30ps time resolution detector for 511 keV photons and…

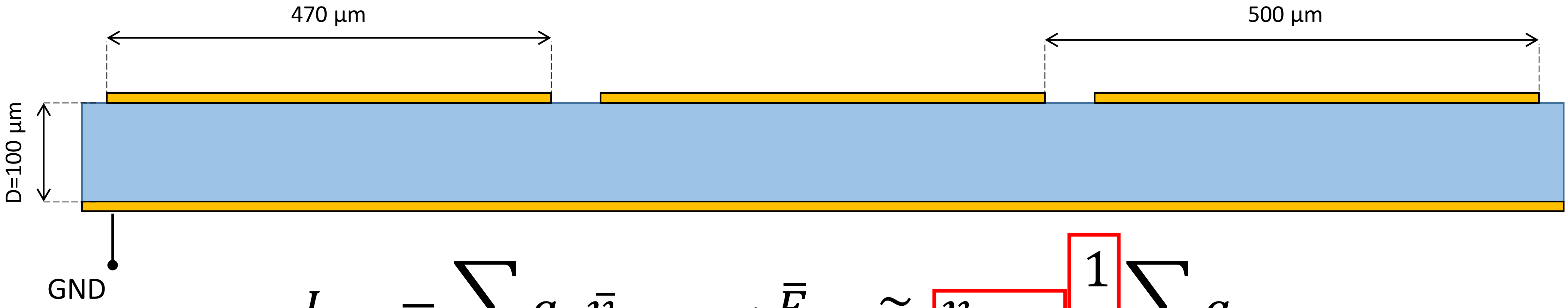
What are the main parameters to improve for the time resolution of semiconductor detectors?

- Read out geometry.
- Electronics noise.
- Charge collection noise.

$$I_{ind} = \sum_i q_i \, \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$

Read out geometry

The "parallel plate" read out is fundamental to guarantee the uniformity of the weighting and the electric field.



$$I_{ind} = \sum_i q_i \, \bar{v}_{drift,i} \cdot \bar{E}_{w,i} \cong v_{drift} \frac{1}{D} \sum_i q_i$$

Scalar, possibly saturated

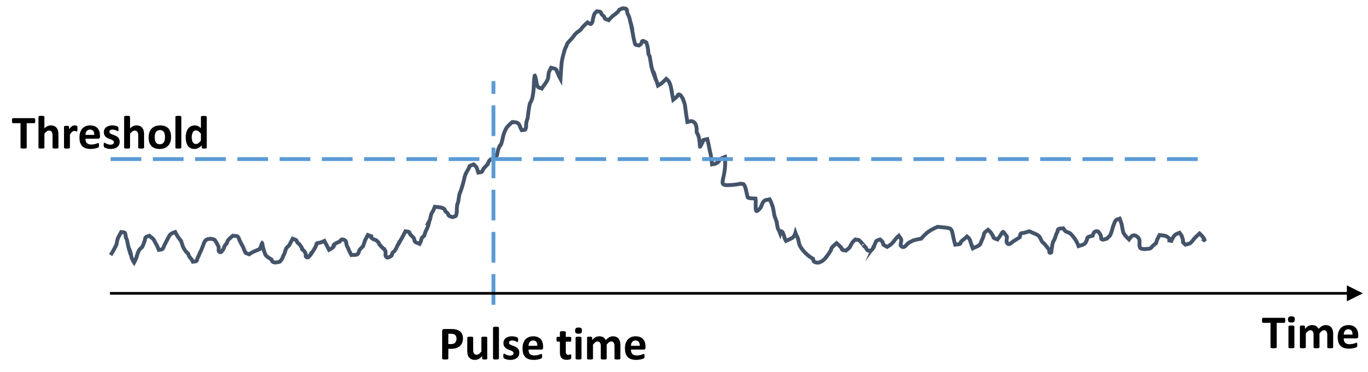
Scalar, uniform

Drawback:

Increase of the pixel capacitance → Larger equivalent noise from the amplifier.

Electronics noise

Detector time resolution depends mostly on the amplifier performance!



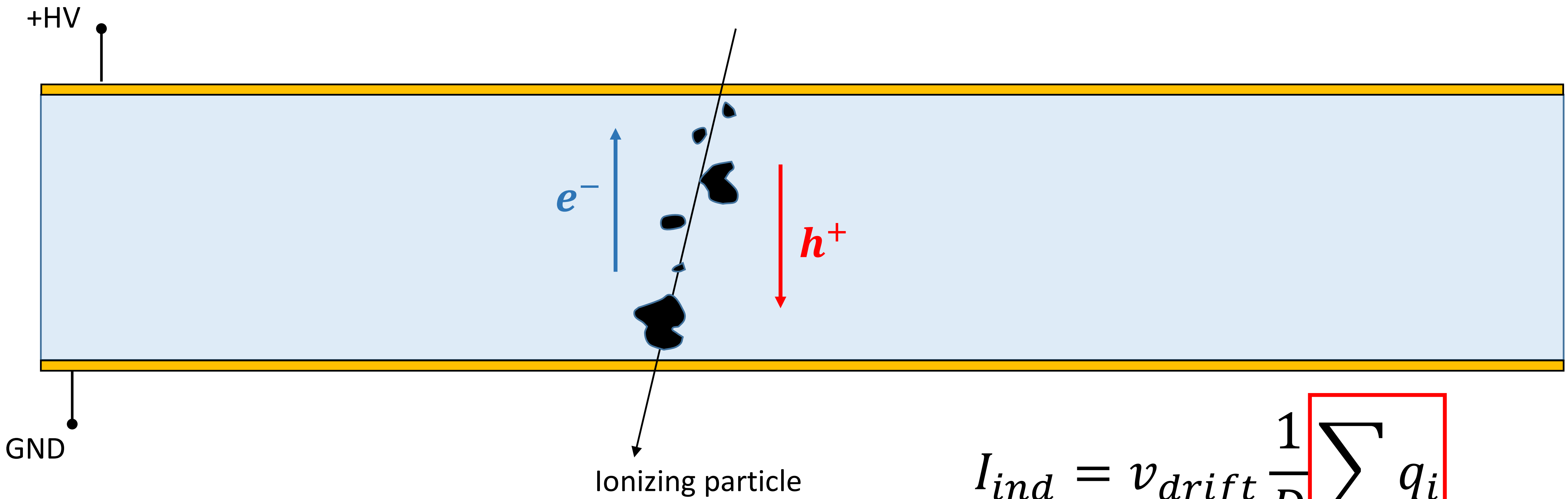
$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \cong \frac{Rise\ Time}{Q/_{ENC}} \qquad \boxed{I_{ind}} = v_{drift}\frac{1}{D}\sum_i q_i$$

1. Fast, low noise electronics: $1\ ns$ rise time, $< 1000\ e^-\ ENC$ on $1\ pF$ capacitance.

   ⮡ High f_t, single transistor preamplifier. ➡ **SiGe HBT** technology.

2. Gain…?

Charge collection noise



$$I_{ind} = v_{drift} \frac{1}{D} \sum_i q_i$$

- Intrinsic limit to the time resolution for a semiconductor detector.
- Can be reduced by reducing the sensor thickness.

Targets of the TT-PET project

1. Make a 30ps time resolution detector for 511 keV photons and…

2. … make it monolithic.

Both sensor and electronics **integrated in the same chip**, in a commercial microelectronics process.

Advantages:

- Simplified interconnections.
- Integrated front end, TDC, logic, serializer.
- Cost reduction

The TT-PET ASIC

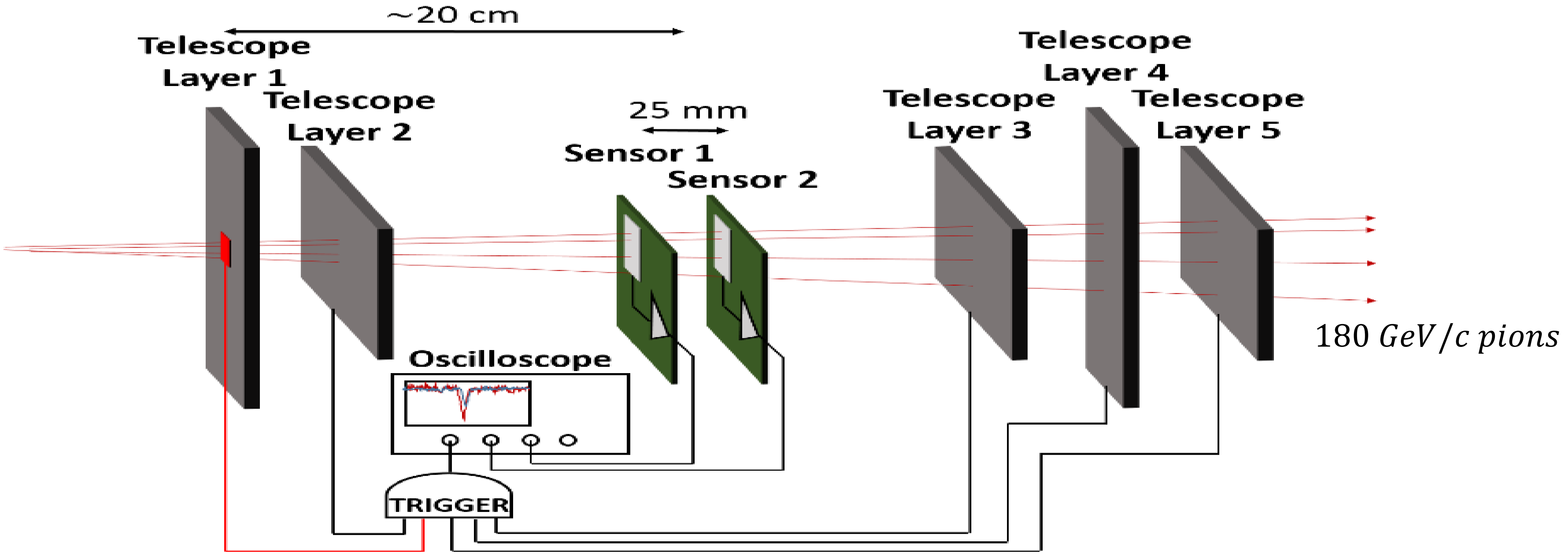
A monolithic silicon pixel detector:

ASIC length	$24\ mm$
ASIC width	$7, 9, 11\ mm$
Pixel Size	$500\ \times 500\ \mu m^2$
Pixel Capacitance (comprised routing)	$750\ fF$
Preamplifier power consumption	$200\ \mu W/channel$
Preamplifier E.N.C.	$600\ e^-\ RMS$
Preamplifier Rise time (10% - 90%)	$800\ ps$
Time resolution for MIPs	$100\ ps\ RMS$
TDC time binning	$20\ ps$
TDC power consumption	$< 1\ mW/channel$

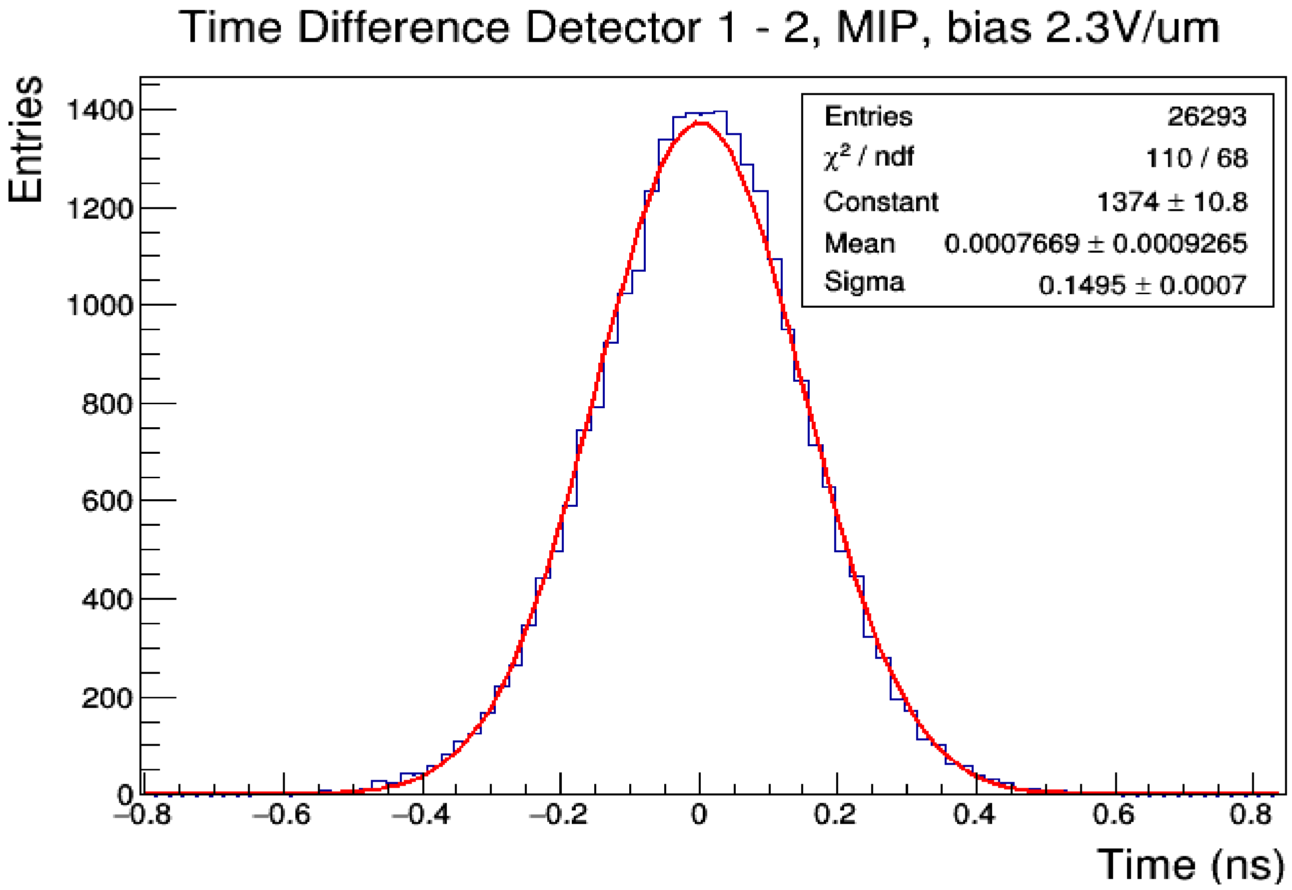
Results from the R&D

Proof of principle

Test of external sensor and custom SiGe HBT preamplifier at H8 beam line at SPS (CERN).



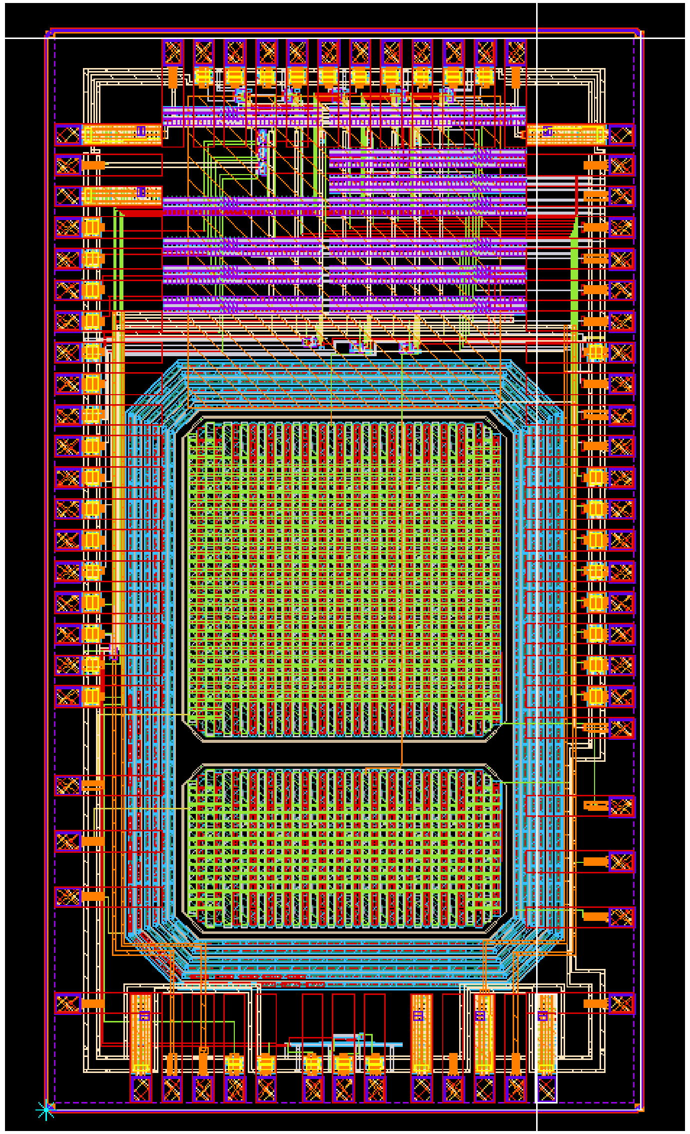
Proof of principle



$$\boldsymbol{\sigma_t = \frac{(150 \pm 1)ps}{\sqrt{2}} = (106 \pm 1)ps.}$$

100ps time resolution measured with MIPs

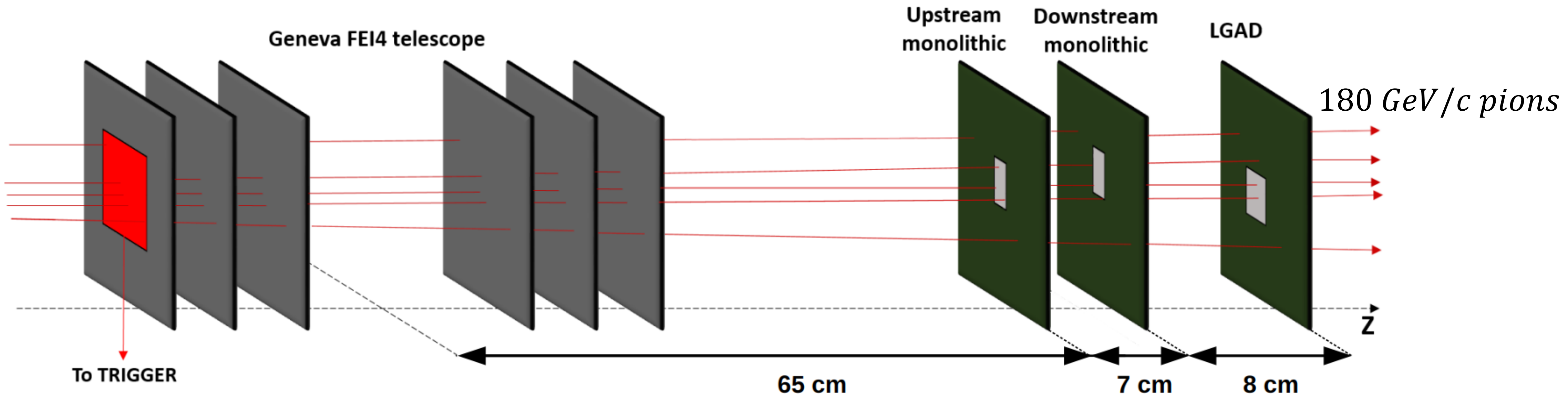
1st monolithic prototype



- Two pixels + amplifier + discriminator in standard IHP SG13S process.
- Pixel size: $900 \times 900\ \mu m^2$ and $900 \times 450\ \mu m^2$.
- Higher wafer resistivity (1 kOhmcm)
- No thinning, no backplane metallization.

1st monolithic prototype

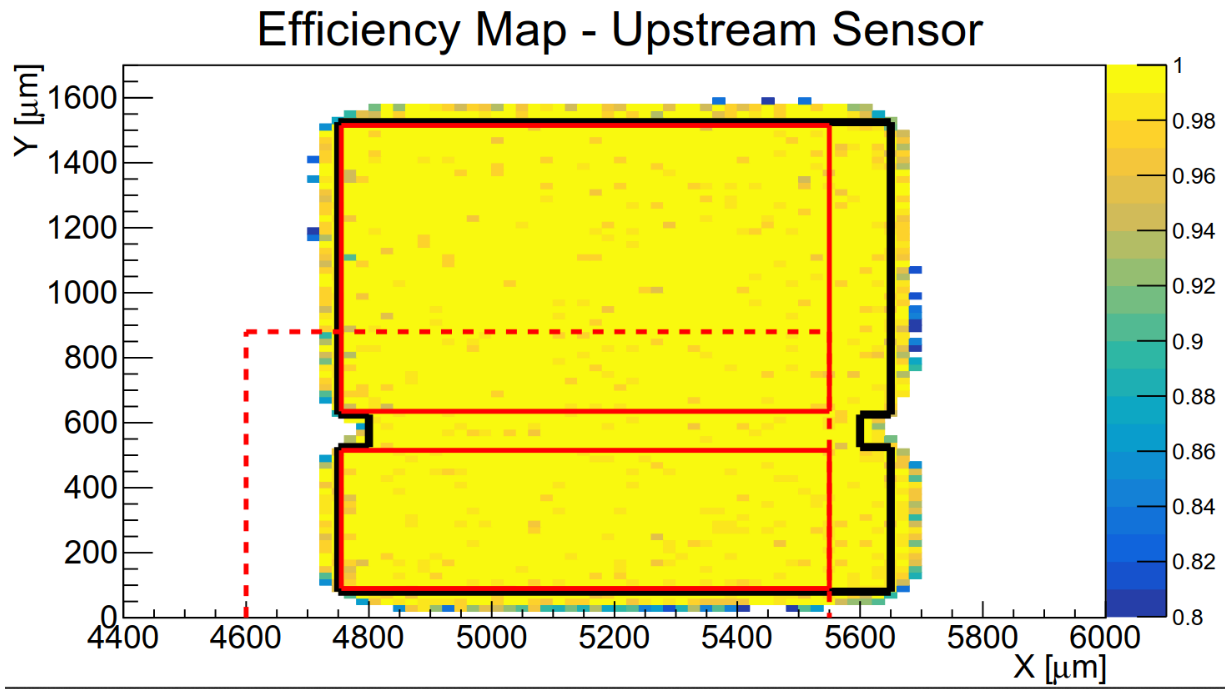
Test of the 1st monolithic prototype at H8 beam line at SPS (CERN).



. Events triggered by the Geneva telescope.

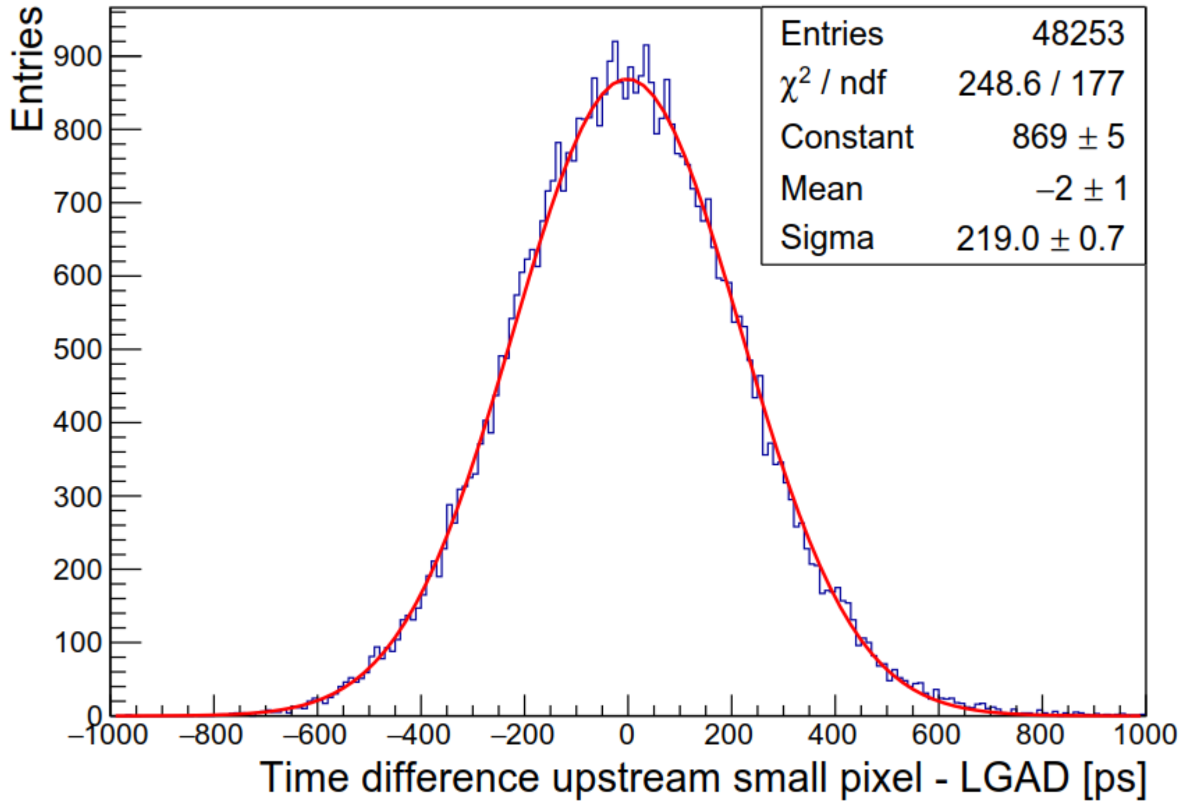
. Typical signal charge: 1.6 fC.

1st monolithic prototype



- Efficiency 99.8%.
- Amplifier $ENC < 600\ electrons\ RMS$.
- Amplifier power consumption: $< 350 \frac{\mu W}{channel}$

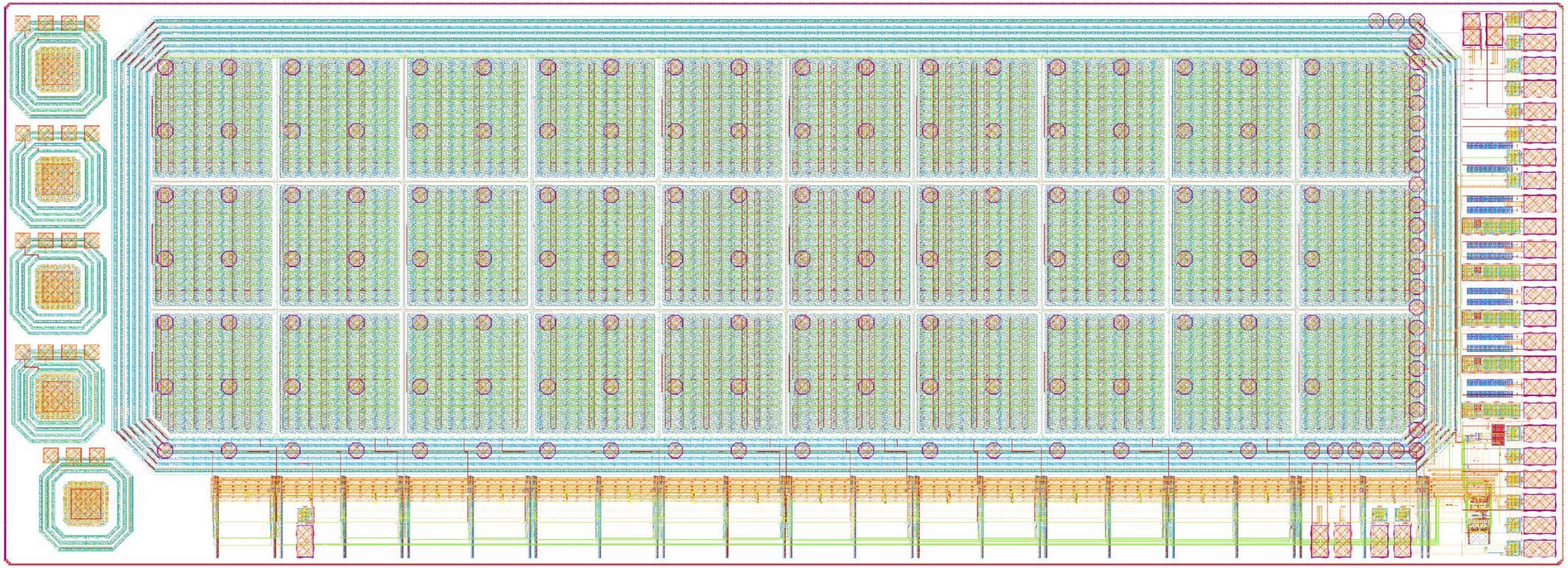
1st monolithic prototype



Time resolution $\sim 220\ ps\ RMS$

(Strongly affected by the absence of fundamental backside processing steps.)

2nd monolithic prototype



- 3×10 matrix, $500 \times 500\ \mu m^2$ pixels.
- Preamplifier, discriminator, 20 ps time resolution TDC, logic, serializer integrated in chip.
- Thinned to $100\ \mu m$.
- Full backside processing.
- **Back from foundry next month.**

Is it possible to go below 100 ps?

Possible approaches:

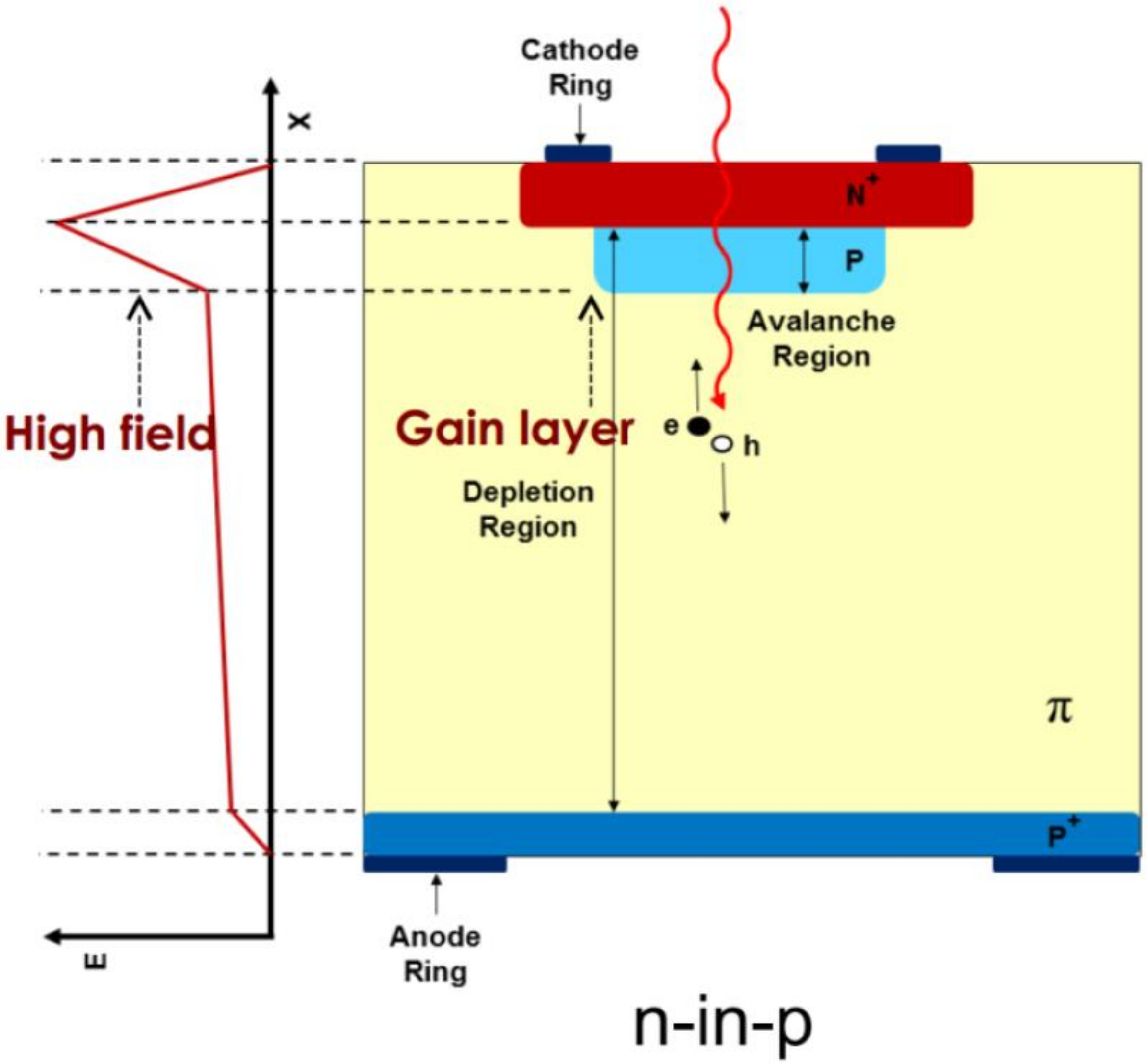
1. Reduce pixel size and sensor thickness.

→ New monolithic design (under study)

2. The Low Gain Avalanche Diode (LGAD).

→ See next slide

The LGAD

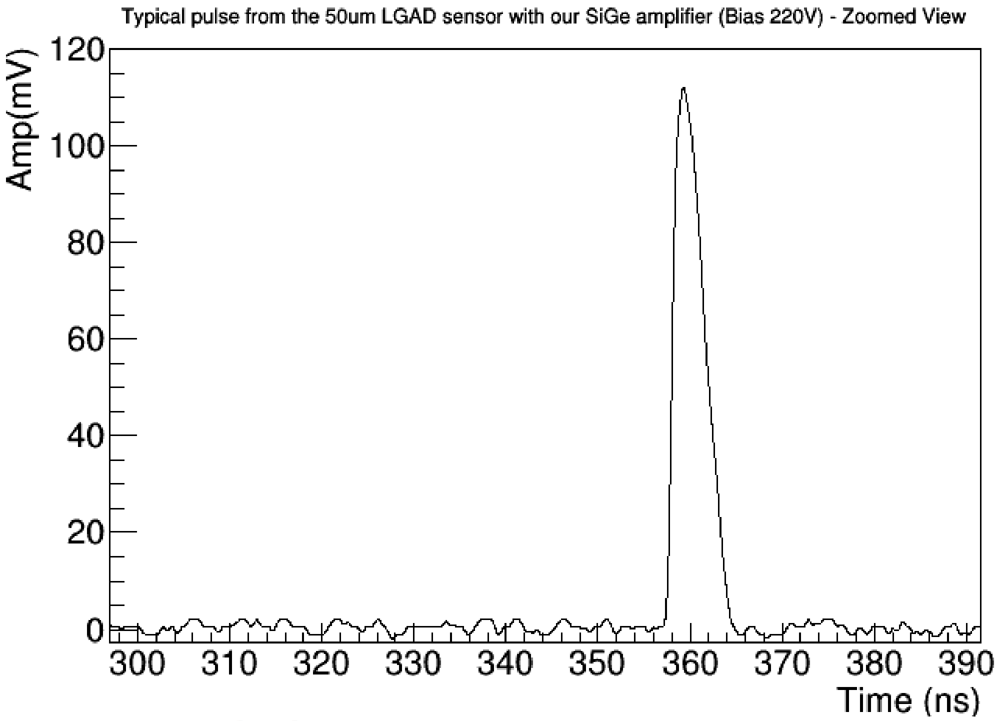


- Proposed as timing detector for the new ATLAS HGTD.
- The is kept low: $G \lesssim 20$

Test beam with CNM LGAD sensors

Our discrete-component SiGe amplifier was coupled to a LGAD produced by CNM and kindly provided by Sebastian Grinstein (IFAE Barcelona)

Thickness: $\sim 45\ \mu m$
PAD size: $1.3\ x\ 1.3\ mm^2$



Performance (bias 220V):

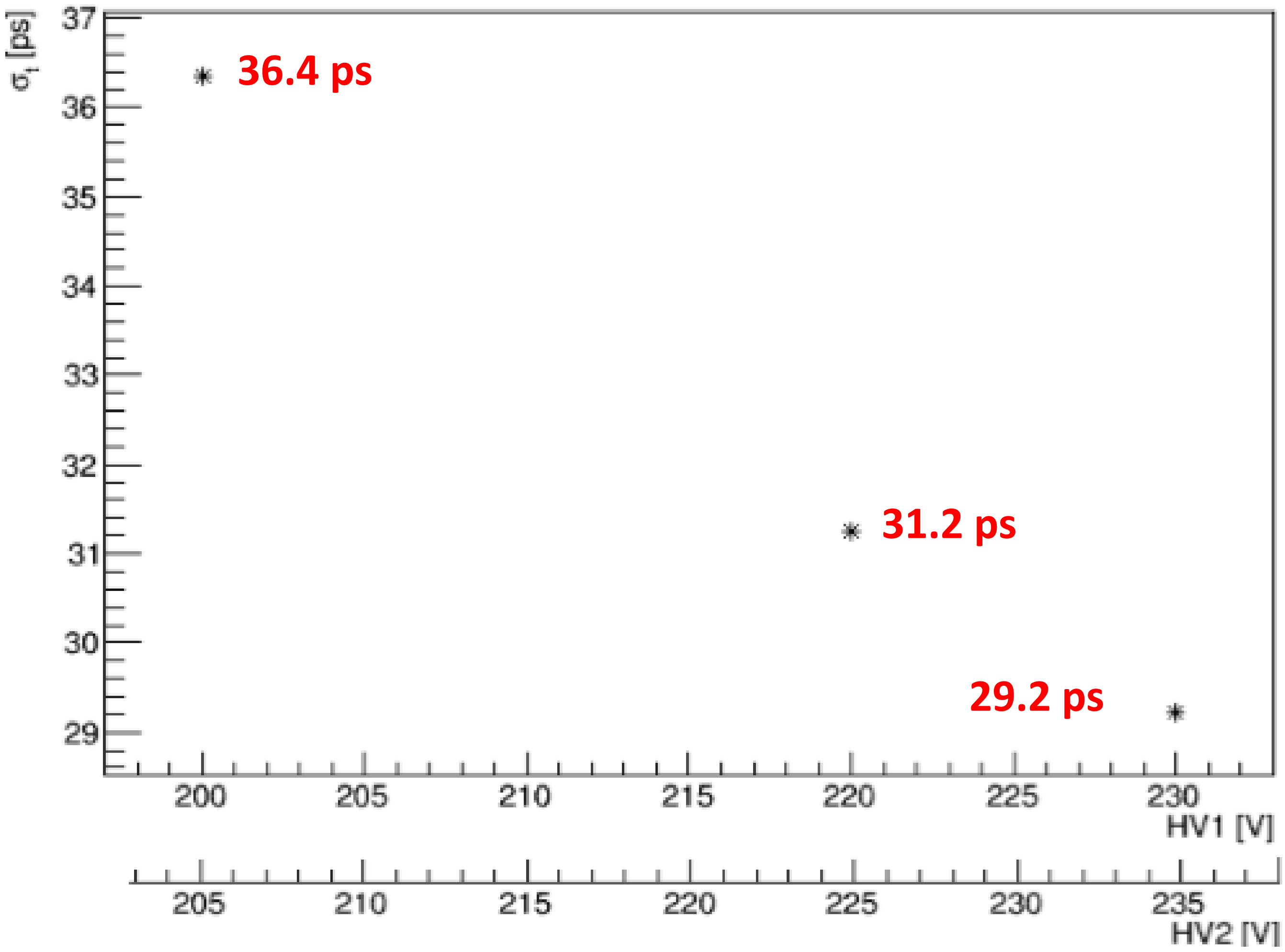
$S/_N = 124$

$t_{rise,20\%-80\%} = 600\ ps$

$\frac{\sigma_V}{dV/_{dt}} = 8\ ps$ ← Expected electronics contribution to the time resolution.

Test beam with CNM LGAD sensors

LGAD time resolution with MIPs measured at H8 beam line at SPS (CERN).



Compatible with expectations from charge collection noise.

Conclusions

- Silicon pixel technology is now able to combine its sub-millimetre space resolution, very high counting rate capability and excellent radiation hardness with a $100\,ps$ time resolution.
- The TT-PET collaboration is implementing this fast pixel detector in a monolithic structure in a SiGe BiCMOS process.
- Even better time resolution is possible introducing a gain layer in the sensitive volume.
- An important part of the expertise at the base of this development comes from the experience obtained on the development of the Resistive Plate Chambers and their front-end electronics.

Extra Material

Minimization of ENC for a fast integrator

$$ENC^2 \propto \left(2q_e I_C + \frac{4kT}{R_P} + i_{na}^2\right) \cdot \tau + \boxed{(4kTR_S + e_{na}^2) \cdot \frac{C_{in}^2}{\tau}} + 4A_f C_{in}^2$$

Dominating term

Excellent performance in terms of series noise for fast shaping are achievable with the BJT technology

$$ENC_{series\ noise} \propto \sqrt{2kT\langle SNI\rangle\left[(C_{in})^2 \frac{h_{ie}}{\beta} + R_{bb} C_{in}^2\right]}$$

Transistor ENC contribution depends on current gain and base spreading resistance

SiGe technology for very low noise and fast amplifiers

Amplifier current gain can be expressed as (NPN BJT)

$$\beta = \frac{i_C}{i_B} = \frac{\tau_p}{\tau_t}$$

$\tau_p = \text{hole recombination time in base}$
$\boldsymbol{\tau_t} = \textbf{electron transit time (E to C)}$

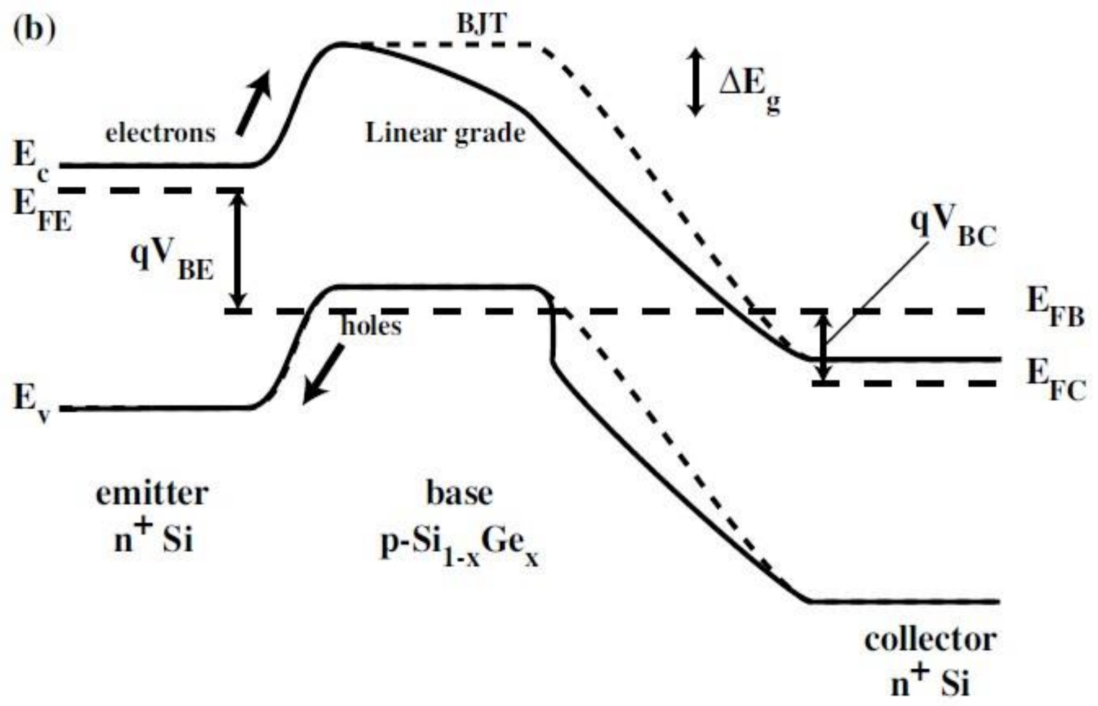
Need to minimize electron transit time in the base

Increase gain ⇒ Reduce base width ⇒ Reducing base doping

Spreading resistance increases!

SiGe technology for very low noise and fast amplifiers

A possible approach: changing the charge transport mechanisms in the base from diffusion to drift.



SiGe heterojunction bipolar transistor technology.

Equivalent to introducing an electric field in the base.

The technology we have chosen is **SG13S from IHP:**

$\beta = 900$

$f_t = 250\ GHz$